

Robust creation of atomic W state in a cavity by adiabatic passage

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We propose two robust schemes to generate controllable (deterministic) atomic W-states of three three-level atoms interacting with an optical cavity and a laser beam. Losses due to atomic spontaneous emissions and to cavity decay are efficiently suppressed by employing adiabatic passage technique and appropriately designed atom-field couplings. In these schemes the three atoms traverse the cavity-mode and the laser beam and become entangled in the free space outside the cavity.

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I. INTRODUCTION

Quantum-state engineering, i.e., active control over the coherent dynamics of suitable quantum-mechanical systems to achieve a preselected state (e.g. entangled states or multi-photon field states) of the system, has become a fascinating prospect of modern physics. The physics of entanglement provides the basis of applications such as quantum information processing and quantum communications. Particles can then be viewed as carriers of quantum bits of information and the realization of engineered entanglement is an essential ingredient of the implementation of quantum gates [1], cryptography [2] and teleportation [3]. The creation of long-lived entangled pairs of atoms may provide reliable quantum information storage. The idea is to apply a set of controlled coherent interactions to the atoms of the system in order to bring them into a tailored entangled state. The problem of controlling entanglement is thus directly connected to the problem of coherent control of population transfer in multilevel systems.

In the case of tripartite entanglement, there are two classes of tripartite entangled states, the GHZ class [4] and the W class, which are inequivalent under stochastic local operation and classical communication [5]. One of the interesting properties of W states [such as $\frac{1}{\sqrt{3}}(|0, 0, 1\rangle + |0, 1, 0\rangle + |1, 0, 0\rangle)$] is that if one particle is traced out, there remains entanglement of the remaining two particles, or if one particle is measured in basis $\{|0\rangle, |1\rangle\}$, then the state of remained two particles is either in a maximally entangled state or in a product state. In the context of cavity QED, the stimulated Raman adiabatic passage (STIRAP) technique has been introduced by Parkins et. al. [6] where the Stokes pulse is replaced by a mode of a high-Q cavity. The advantage of STIRAP is the robustness of its control with respect to the precise tuning of pulse areas, pulse delay, pulse widths, pulse shapes, and detunings. In Λ -type systems, fractional STIRAP (F-STIRAP) is a variation of STIRAP [7] which allows the creation of any preselected coherent superposition of the two degenerate ground states [8]. The half-STIRAP process (F-STIRAP with final half population of two ground states) has also been studied in an optical cavity to prepare atom-photon and atom-atom entanglement [9, 10].

In cavity QED, the schemes for generating n-partite W states are two types: 1) n-atom, and 2) n-cavity W states. The long-lived atomic W states is more robust than the cavity W states against the cavity damping. In this context, there are several schemes discussing the preparation of atomic W states [11, 12, 13, 14, 15]. The entangled W state of two-level atoms using pulse area technique in a cavity has been proposed in [11, 12]. However the pulse area technique is not robust with respect to the velocity of the atoms and the exact-resonance condition. Another scheme to entangle traveling atoms in the atom-cavity-laser system via adiabatic passage has been proposed in Ref. [15]. However this scheme requires to turn off the laser field when the two atoms have equal coupling with the cavity-mode, which is very difficult from the experimental point of view. Moreover this scheme requires to compensate a dynamical Stark shift which is also very difficult in a real experiment. In the scheme of Ref. [13], n-atom W state is generated in $n + 1$ distant optical cavity connected by n optical fibers, based on the method proposed in [10] and STIRAP process. The STIRAP technique is also used in [14] to generate W state in a two-mode optical cavity which needs initially one photon to be present in one of the cavity modes.

In this paper we propose an alternative method to create the W state of three traveling atoms interacting with an optical cavity and a laser beam, based on 3-level interactions in a Λ -configuration. This method is based on the coherent creation of superposition of atom-atom-atom-cavity states via fractional STIRAP and multilevel STIRAP [10, 18], that keeps the cavity-mode and the excited atomic states weakly populated during the whole interaction in the adiabatic limit and for a sufficiently strong cavity coupling.

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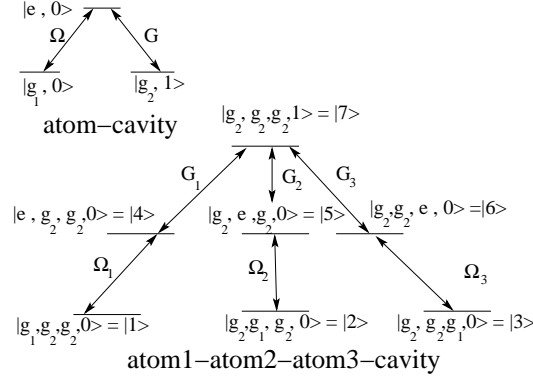


FIG. 1: Linkage pattern of the system corresponding to the effective Hamiltonian.

II. CONSTRUCTION OF THE MODEL

Figure 2 represents the linkage pattern of the atom-cavity-laser system. The laser pulse associated to the Rabi frequency $\Omega(t)$ couples the states $|g_1\rangle$ and $|e\rangle$, and the cavity-mode with Rabi frequency $G(t)$ couples the states $|e\rangle$ and $|g_2\rangle$. The Rabi frequencies $\Omega(t)$ and $G(t)$ are chosen real without loss of generality. These two fields interact with the atom with a time delay, each of the fields is in one-photon resonance with the respective transition. The semiclassical Hamiltonian of this system in the resonant approximation where

$$|\Omega_0|, |G_0| \ll \omega_e, \omega_C, \quad (1)$$

with Ω_0, G_0 the peak values of the Rabi frequencies, can then be written as ($\hbar = 1$):

$$H(t) = \sum_{i=1,2,3} [\omega_e |e\rangle_{ii} \langle e| + (G_i(t) a |e\rangle_{ii} \langle g_2| + \text{H.c.}) + (\Omega_i(t) |g_1\rangle_{ii} \langle e| + \text{H.c.})] + \omega_C a^\dagger a, \quad (2)$$

where the subscript i on the states denotes the three atoms, a is the annihilation operator of the cavity mode, ω_e is the energy of the atomic excited state ($\omega_{g_1} = \omega_{g_2} = 0$), and ω_C is the frequency of the cavity mode taking resonant $\omega_C = \omega_L = \omega_e$. In the following we consider the state of the atom1-atom2-atom3-cavity system as $|A1, A2, A3, n\rangle$ where $\{A1, A2, A3 = g_1, e, g_2\}$, and $\{n = 0, 1\}$ is the number of photons in the cavity-mode. Regarding Figure 1, the subspace \mathcal{S} generated by the states $\{|g_1, g_2, g_2, 0\rangle, |e, g_2, g_2, 0\rangle, |g_2, g_2, g_2, 1\rangle, |g_2, e, g_2, 0\rangle, |g_2, g_1, g_2, 0\rangle, |g_2, g_2, e, 0\rangle, |g_2, g_2, g_1, 0\rangle\}$ is decoupled under H from the rest of the Hilbert space of the system. If we consider the initial state of the system as $|g_1, g_2, g_2, 0\rangle$ or $|g_2, g_2, g_2, 1\rangle$, the effective Hamiltonian of the system in the subspace \mathcal{S} will be

$$H^{\text{eff}}(t) := \begin{pmatrix} 0 & 0 & 0 & \Omega_1(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Omega_2(t) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Omega_3(t) & 0 \\ \Omega_1(t) & 0 & 0 & 0 & 0 & 0 & G_1(t) \\ 0 & \Omega_2(t) & 0 & 0 & 0 & 0 & G_2(t) \\ 0 & 0 & \Omega_3(t) & 0 & 0 & 0 & G_3(t) \\ 0 & 0 & 0 & G_1(t) & G_2(t) & G_3(t) & 0 \end{pmatrix}, \quad (3)$$

The associated dynamics is determined by the Schrödinger equation $i \frac{\partial}{\partial t} |\Phi(t)\rangle = H^{\text{eff}}(t) |\Phi(t)\rangle$.

III. THREE-ATOM W STATE

In this section, the goal is to transform the initial state of the system, at the end of interaction, into an atomic W state

$$\begin{aligned} |\Phi(t_f)\rangle &= \frac{1}{\sqrt{3}} (|g_1, g_2, g_2, 0\rangle + |g_2, g_1, g_2, 0\rangle + |g_2, g_2, g_1, 0\rangle) \\ &= \frac{1}{\sqrt{3}} (|g_1, g_2, g_2\rangle + |g_2, g_1, g_2\rangle + |g_2, g_2, g_1\rangle) |0\rangle, \end{aligned} \quad (4)$$

where the cavity-mode state factorizes and is left in the vacuum state. The qubits are stored in the two degenerate ground states of the atoms. The decoherence due to atomic spontaneous emission is produced if the states $\{|e, g_2, g_2, 0\rangle, |g_2, e, g_2, 0\rangle, |g_2, g_2, e, 0\rangle\}$ are populated, and the cavity decay occurs if the state $|g_2, g_2, g_2, 1\rangle$ is populated during the adiabatic evolution of the system. Therefore we will design the Rabi frequencies $\{\Omega_1(t), G_1(t), \Omega_2(t), G_2(t), \Omega_3(t), G_3(t)\}$ in our scheme such that these states are not populated during the whole dynamics. We remark that we will use a resonant process without any adiabatic elimination.

A. Scheme 1

In the first scheme, the system is taken to be initially in the state $|\Phi(t_i)\rangle = |g_1, g_2, g_2, 0\rangle$. Using fractional STIRAP process, and Rabi frequencies of the fields as $G_1(t) \sim G_2(t) = G_3(t) = G(t)$, $\Omega_2(t) = \Omega_3(t) = \Omega(t)$. We try to transfer the final population of the system to the desired W state. In this case, one of the instantaneous eigenstates (the three-atom dark state) of $H^{\text{eff}}(t)$ which corresponds to a zero eigenvalue is [16]:

$$|D(t)\rangle = C \left(|g_1, g_2, g_2, 0\rangle - \frac{\Omega_1}{G} |g_2, g_2, g_2, 1\rangle + \frac{\Omega_1}{\Omega} |g_2, g_1, g_2, 0\rangle + \frac{\Omega_1}{\Omega} |g_2, g_2, g_1, 0\rangle \right), \quad (5)$$

where C is a normalization factor. The possibility of decoherence-free generation of W state arises from the following behavior of the dark state:

$$t_i < t < t_f, \quad G(t) \gg \Omega_1(t), \Omega(t), \quad (6a)$$

$$|D(t)\rangle = C \left(|g_1, g_2, g_2, 0\rangle + \frac{\Omega_1}{\Omega} |g_2, g_1, g_2, 0\rangle + \frac{\Omega_1}{\Omega} |g_2, g_2, g_1, 0\rangle \right),$$

$$\lim_{t \rightarrow t_i} \frac{\Omega_1(t)}{\Omega(t)} = 0, \quad |D(t_i)\rangle = |g_1, g_2, g_2, 0\rangle \quad (6b)$$

$$\lim_{t \rightarrow t_f} \frac{\Omega_1(t)}{\Omega(t)} = 1, \quad (6c)$$

$$|D(t_f)\rangle = \frac{1}{\sqrt{3}} \left(|g_1, g_2, g_2, 0\rangle + |g_2, g_1, g_2, 0\rangle + |g_2, g_2, g_1, 0\rangle \right).$$

Equations (6b) and (6c) are known as f-STIRAP conditions [8, 9, 10], and the condition (6a) guarantees the absence of population in the state $|g_2, g_2, g_2, 1\rangle$ during the time-evolution of the system [17]. Equation (6c) means that the Rabi frequencies fall off in a constant ratio, during the time interval where they are non-negligible. We remark that this formulation opens up the possibility to implement f-STIRAP with Gaussian pulses. The goal in the following is to show that such a pulse sequence can be designed in a cavity by an appropriate choice of the parameters. In an optical cavity, the spatial variation of the atom-field coupling for the maximum coupling TEM₀₀ mode, resonant with the $|e\rangle \leftrightarrow |g_2\rangle$ atomic transition, is given by

$$G(x, y, z) = G_0 e^{-(x^2+y^2)/W_C^2} \cos\left(\frac{2\pi z}{\lambda}\right), \quad (7)$$

where W_L is the waist of the cavity mode, and $G_0 = -\mu\sqrt{\omega_C/(2\epsilon_0 V_{\text{mode}})}$ with μ and V_{mode} respectively the dipole moment of the atomic transition and the effective volume of the cavity mode. The spatial variation of the atom-laser coupling for the laser beam of Fig. 2 is

$$\Omega(x, z) = \Omega_0 e^{-(x^2+z^2)/W_L^2}, \quad (8)$$

where W_L is the waist of the laser beam, and $\Omega_0 = -\mu\mathcal{E}/2$ with \mathcal{E} the amplitude of the laser field. Figure 2 shows a situation where the first atom, initially in the state $|g_1\rangle$, goes with velocity v (on the $y = 0$ plane at $z = z_0$ line) through an optical cavity initially in the vacuum state $|0\rangle$ and then encounters the laser beam, which is parallel to the y axis (orthogonal to the cavity axis and the trajectory of the atom). The laser beam is resonant with the $|e\rangle \leftrightarrow |g_1\rangle$ transition. The distance between the center of the cavity and the laser axis is d . The second and the third atoms, initially in the state $|g_2\rangle$ and synchronized with the first one, move with the same velocity v on the $y = 0$ plane at $z = 0$ in the opposite direction with respect to the first atom. The traveling atoms encounter the time-dependent and delayed Rabi frequencies of the cavity-mode and the laser fields as follows:

$$G_1(t) = G_0 e^{-(vt)^2/W_C^2} \cos\left(\frac{2\pi z_0}{\lambda}\right), \quad (9a)$$

$$\Omega_1(t) = \Omega_0 e^{-z_0^2/W_L^2} e^{-(vt-d)^2/W_L^2}, \quad (9b)$$

$$G_2(t) = G_3(t) = G_0 e^{-(vt)^2/W_C^2}, \quad (9c)$$

$$\Omega_2(t) = \Omega_3(t) = \Omega_0 e^{-(vt+d)^2/W_L^2} \quad (9d)$$

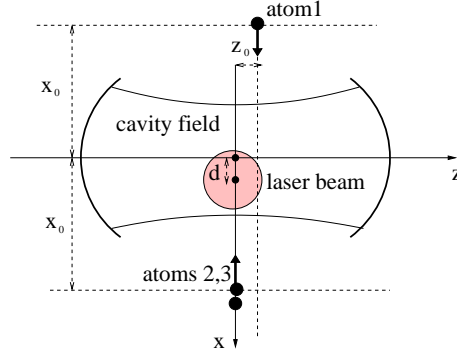


FIG. 2: (color online). Geometrical configuration of the atoms-cavity-laser system in scheme 1. The propagation direction of the laser beam is parallel to y axis and perpendicular to the page.

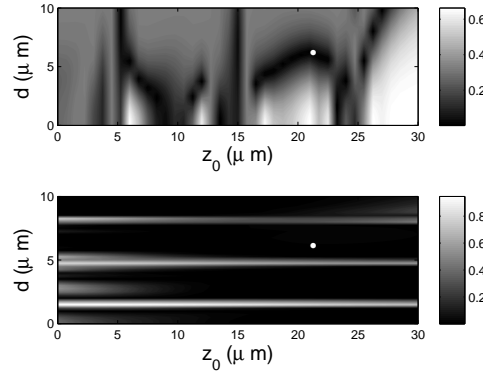


FIG. 3: Top panel: contour plot at the final time t_f of $|\frac{1}{3} - P_{|g_1, g_2, g_2, 0\rangle}(t_f)|$ as a function of z_0 and d (black areas correspond to approximately 33% population transfer) with the pulse parameters as $W_L = 20 \mu\text{m}$, $W_C = 40 \mu\text{m}$, $v = 2 \text{ m/s}$, $\lambda = 780 \text{ nm}$, $\Omega_0 = 20(v/W_L)$, $G_0 = 100(v/W_C)$. Bottom panel: The same plot for the sum of the final populations in intermediate states $P_{|g_2, e, g_2, 0\rangle}(t_f) + P_{|e, g_2, g_2, 1\rangle}(t_f) + P_{|g_2, g_2, e, 0\rangle}(t_f) + P_{|g_2, g_2, g_2, 1\rangle}(t_f)$ where black areas correspond to approximately zero population. The white dot shows specific values of z_0 and d used in Fig. 4 to obtain a fractional STIRAP process.

where the time origin is defined when the atoms meet the center of the cavity at $x = y = 0$. The appropriate values of z_0 and d that lead to the f-STIRAP process can be extracted from a contour plot of the final population $P_{|g_1, g_2, g_2, 0\rangle}(t_f) := |\langle g_1, g_2, g_2, 0 | \Phi(t_f) \rangle|^2$ as a function of z_0 and d that we calculated numerically (see Fig. 3). The white dot in Fig. 3 shows values of z_0 and d to obtain an f-STIRAP process with the final populations of $P_{|g_1, g_2, g_2, 0\rangle}(t_f) \simeq P_{|g_2, g_1, g_2, 0\rangle}(t_f) \simeq P_{|g_2, g_2, g_1, 0\rangle}(t_f) \simeq \frac{1}{3}$, and zero population of the other states. Figure 4 shows (a) the time dependent Rabi frequencies of fractional STIRAP for three atoms using the specific values of z_0 and d in Fig. 3, and (b) the time evolution of populations which shows $\frac{1}{3}$ population for the states $|g_1, g_2, g_2, 0\rangle$, $|g_2, g_1, g_2, 0\rangle$, $|g_2, g_2, g_1, 0\rangle$ and zero population for the states $|e, g_2, g_2, 0\rangle$, $|g_2, e, g_2, 0\rangle$, $|g_2, g_2, e, 0\rangle$, $|g_2, g_2, g_2, 1\rangle$ at the end of the interaction. This case corresponds to the generation of the maximally entangled W state (4) by adiabatic passage.

B. Scheme 2

In the second scheme, the system is taken to be initially in the state $|\Phi(t_i)\rangle = |g_2, g_2, g_2, 1\rangle$. Using multilevel STIRAP process [18], and Rabi frequencies of the fields as $G_1(t) = G_2(t) = G_3(t) = G(t)$, $\Omega_1(t) = \Omega_2(t) = \Omega_3(t) = \Omega(t)$, We try to transfer the final population of the system to the target W state. In this case, the dark state of $H^{\text{eff}}(t)$ is:

$$|D(t)\rangle = C \left(|g_1, g_2, g_2, 0\rangle - \frac{\Omega}{G} |g_2, g_2, g_2, 1\rangle + |g_2, g_1, g_2, 0\rangle + |g_2, g_2, g_1, 0\rangle \right), \quad (10)$$

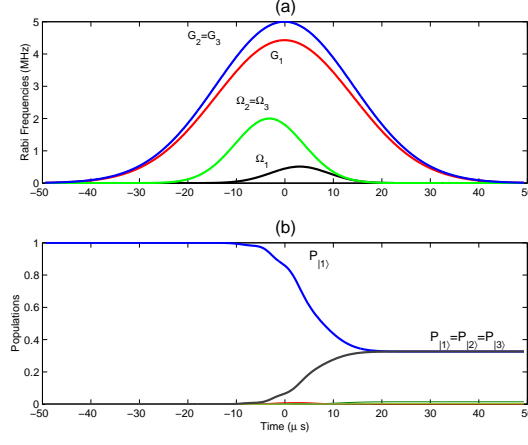


FIG. 4: (color online). (a): Rabi frequencies of the cavity-mode and the laser field for three atoms in scheme 1, using the pulse parameters of Fig. 3. (b): Time evolution of the populations which represents a three-atom fractional-STIRAP. The population of the states $\{|e, g_2, g_2, 0\rangle, |g_2, e, g_2, 0\rangle, |g_2, g_2, g_2, 1\rangle, |g_2, g_2, e, 0\rangle\}$ is almost zero during the whole dynamics.

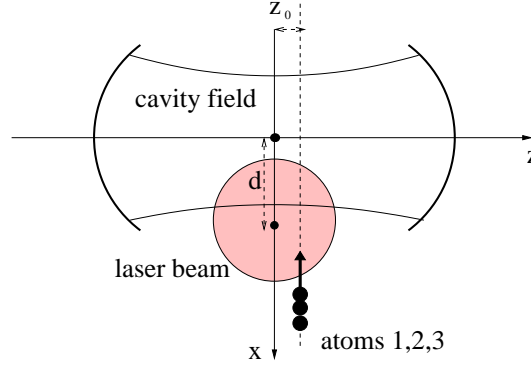


FIG. 5: The proposed geometry of the cavity and the laser fields in xz plane as well as the trajectory of the atoms for generation of the atomic W state in scheme 2. The three atoms initially in the ground state $|g_2\rangle$ arrive simultaneously at the center of the cavity, initially in the state $|1\rangle$. These atoms encounter the sequence laser-cavity on the line $z = z_0$.

The possibility of decoherence-free generation of W state arises from the following behavior of this dark state:

$$\lim_{t \rightarrow t_i} G(t) = 0, \quad |D(t_i)\rangle = |g_2, g_2, g_2, 1\rangle, \quad (11a)$$

$$\lim_{t \rightarrow t_f} \Omega(t) = 0, \quad |D(t_f)\rangle = \frac{1}{\sqrt{3}}(|g_1, g_2, g_2, 0\rangle + |g_2, g_1, g_2, 0\rangle + |g_2, g_2, g_1, 0\rangle). \quad (11b)$$

In this scheme, we consider a situation where the three atoms, initially in the ground state $|g_2\rangle$, are going simultaneously to interact with the laser and cavity-mode fields on the line $z = z_0$ (see Fig. 5), but through a multilevel STIRAP process. The initial state of the cavity mode, despite the first scheme, is $|1\rangle$. The atoms encounter time-dependent and delayed Rabi frequencies given by

$$G_1(t) = G_2(t) = G_3(t) = G(t) = G_0 e^{-(vt)^2/W_C^2} \cos\left(\frac{2\pi z_0}{\lambda}\right), \quad (12a)$$

$$\Omega_1(t) = \Omega_2(t) = \Omega_3(t) = \Omega(t) = \Omega_0 e^{-z_0^2/W_L^2} e^{-(vt+d)^2/W_L^2}. \quad (12b)$$

By multilevel STIRAP process [18], with the sequence of laser-cavity (see Fig. 6), we can transfer the population from the initial state $|g_2, g_2, g_2, 1\rangle$ to the final state (4). Since the cavity-mode state factorizes and is left in the vacuum state, there is no projection noise when one traces over the unobserved cavity field, and the cavity is ready to prepare another atomic entangled state.

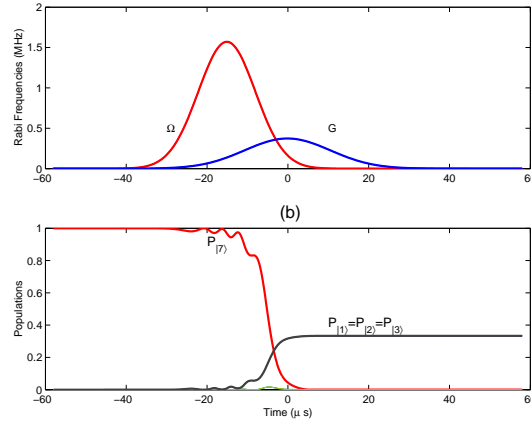


FIG. 6: (color online). (a): Rabi frequencies of the cavity-mode and the laser fields (see Eqs. (12a, 12b)) for three atoms with the pulse parameters as $v = 2$ m/s, $W_L = 20\mu\text{m}$, $W_C = 30\mu\text{m}$, $\lambda = 780$ nm, $\Omega_0 = 20$ MHz, $G_0 = 0.5$ MHz, $z_0 = 31.9\mu\text{m}$, $d = 30\mu\text{m}$. (b): Time evolution of the populations which represents a three-atom STIRAP, and final population of $1/3$ in the states $\{|g_1, g_2, g_2, 0\rangle, |g_2, g_1, g_2, 0\rangle, |g_2, g_2, g_1, 0\rangle\}$. We observe that the states $|e, g_2, g_2, 0\rangle, |g_2, e, g_2, 0\rangle, |g_2, g_2, e, 0\rangle, |g_2, g_2, g_2, 1\rangle$ are not populated during the whole dynamics.

IV. CONCLUSION

we have proposed two robust and decoherence-free schemes to generate atomic entangled W state, using the f-STIRAP and multilevel STIRAP techniques in Λ -systems. These schemes are robust with respect to variations of the velocity of the atoms v , of the peak Rabi frequencies G_0, Ω_0 and of the field detunings. The first scheme is not robust with respect to the parameters d, z_0 , describing the relative positions of the laser beam and the cavity, shown in Fig. 2, and the second scheme requires initially one photon in the cavity mode. Assuming Gaussian pulse profiles for $\Omega(t)$ and $G(t)$ of widths $T_L = W_L/v$ and $T_C = W_C/v$ respectively, the sufficient condition of global adiabaticity [7] is $\Omega_0 T_L, G_0 T_C \gg 1$. Our schemes can be implemented in an optical cavity with $G_0 \sim \kappa \sim \Gamma$. In the second scheme, G_0 can be smaller than Ω_0 ($G_0 = \frac{1}{40}\Omega_0$ in Fig. 6), but in the first one, the necessary condition to suppress the cavity decoherence is $G_0 \gg \Omega_0$ which is satisfied in practice for $G_0 \sim 3\Omega_0$ (see Fig. 4). In scheme 1, decoherence channels are suppressed during the whole evolution of the system, while in the second scheme, decoherence is only related to the initial photon of the cavity mode. In these schemes, as opposed to other schemes, we do not need to fix the atoms inside the optical cavity. We can generalize this process to generate N -atom W state with $N > 3$.

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- [1] A. Ekert and R. Jozsa, Rev. Mod. Phys. **68**, 3733 (1997).
 - [2] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
 - [3] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70**, 1895 (1993).
 - [4] D. M. Greenberger, M. Horne, and A. Zeilinger, *Bell's Theorem, Quantum Theory, and Conceptions of the Universe* (Kluwer, Dordrecht, 1989).
 - [5] W. Dur, G. Vidal, and J. I. Cirac, Phys. Rev. A **62**, 062314 (2000).
 - [6] A. S. Parkins, P. Marte, P. Zoller, and H. J. Kimble, Phys. Rev. Lett. **71**, 3095 (1993).
 - [7] N. V. Vitanov, T. Halfmann, B. W. Shore, and K. Bergmann, Annu. Rev. Phys. Chem. **52**, 763 (2001).
 - [8] N. V. Vitanov, K. A. Suominen, and B. W. Shore, J. Phys. B **32**, 4535 (1999).
 - [9] M. Amnat-Talab, S. Guérin, N. Sangouard, and H. R. Jauslin, Phys. Rev. A **71**, 023805 (2005).
 - [10] M. Amnat-Talab, S. Guérin, and H. R. Jauslin, Phys. Rev. A **72**, 012339 (2005).
 - [11] Z. J. Deng, M. Feng, and K. L. Gao, Phys. Rev. A **73**, 014302 (2006).
 - [12] G. C. Guo and Y. S. Zhang, Phys. Rev. A **65**, 054302 (2002).
 - [13] L. B. Chen, M. Y. Ye, G. W. Lin, Q. H. Du, and X. M. Lin, Phys. Rev. A **76**, 062304 (2007).
 - [14] A. Biswas and G. S. Agarwal, J. Mod. Opt. **51**, 1627 (2004).

- [15] C. Marr, A. Beige, and G. Rempe, Phys. Rev. A **68**, 033817 (2003).
- [16] T. Pellizzari, S. A. Gardiner, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **75**, 3788 (1995).
- [17] N. V. Vitanov, Phys. Rev. A **58**, 2295 (1998).
- [18] R. G. Unanyan, B. W. Shore, and K. Bergmann, Phys. Rev. A **63**, 043401 (2001).